A GLOBAL APOLLO PROGRAMME TO COMBAT CLIMATE CHANGE

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EXECUTIVE SUMMARY

I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.

THOMAS EDISON (1931)[1]

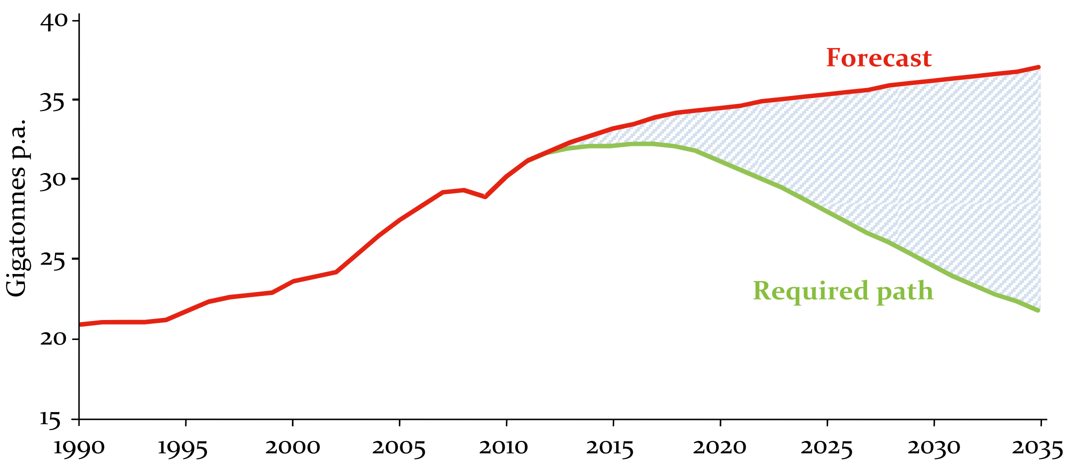
We are in danger

Climate change threatens us with increased risk of drought, flood and tempest, leading to mass migration and conflict. These dangers can be limited if the rise in temperature is less than 2˚C above the pre-industrial level. And in 2010 world leaders agreed at Cancun to act to achieve that limit.

But the commitments made since then have little chance of achieving that target. Even if every promise was carried out, carbon-dioxide emissions will continue to rise (see Figure). By 2035 the concentration of carbon dioxide in the atmosphere will exceed the critical level for a 2˚C rise in temperature and on current policies the temperature will eventually reach 4˚C above the pre-industrial level. This is the central forecast, implying a 50% chance of still higher temperatures.

We must take action to prevent this, by radically cutting the world's output of carbon dioxide (see Figure). We must reduce the use of energy and we must make the energy we use clean i.e. free of carbon-dioxide emissions. This Report is about how to make energy clean.

Energy-related CO2 emissions



One thing would be enough…

One thing would be enough to make it happen: if clean energy became less costly to produce than energy based on coal, gas or oil. Once this happened, the coal, gas and oil would simply stay in the ground. Until then fossil-fuel-based energy should of course be charged for the damage it does, but ultimately energy should become able to compete directly on cost. How quickly could this happen?

The challenge is a technological one and it requires a major focus from scientists and engineers. The need is urgent. Greenhouse gases once emitted stay with us for well over a century. It would also be tragic if we now over-invested in polluting assets which rapidly became obsolete.

In the past, when our way of life has been threatened, governments have mounted major scientific programmes to overcome the challenges. In the Cold War the Apollo Programme placed a man on the moon. This programme engaged many of the best minds in America. Today we need a global Apollo programme to tackle climate change; but this time the effort needs to be international. We need a major international scientific and technological effort, funded by both public and private money. This should be one key ingredient among all the many other steps needed to tackle climate change which have been so well set out in the latest reports of the IPCC.[2]

We need a major programme of publicly-funded research

Most of the main technological advances of the last hundred years have derived from publicly funded R&D – the computer, semiconductors, the internet, genetic sequencing, broadband, satellite communications, and nuclear power. Yet in the case of climate change the main focus has been on incentives for the private sector: carbon prices, feed-in tariffs, and regulatory standards. These are of course essential and must remain central to the climate change agenda for many decades. But publicly funded RD&D (research, development and demonstration) is also vital.

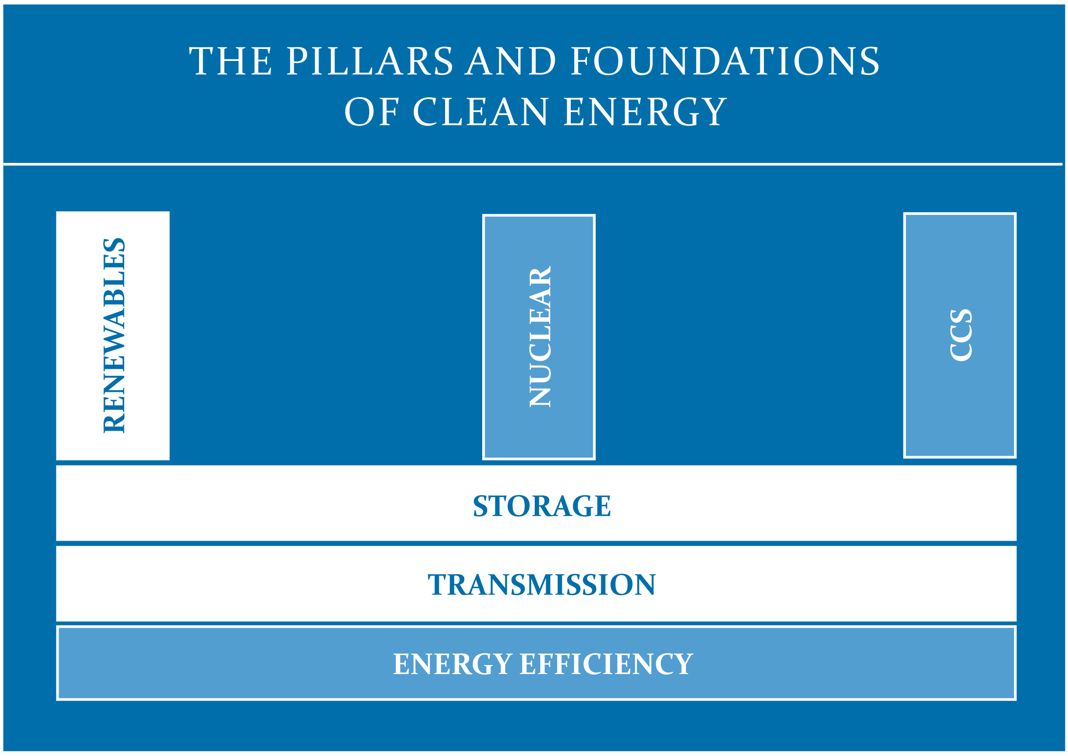
It has been starved. Worldwide, publicly-funded RD&D on renewable energy is under 2% of the total of publicly funded research and development – only around $6 billion in total.[3, 4] This is hardly commensurate with the gravity of the threat we face.

So we need a quite new priority for the discovery of new, cheaper ways to produce, store and distribute clean energy. At the same time it is right to subsidise the supply of clean energy until its cost comes down. But the $6 billion that governments spend on renewable RD&D is far too low. It compares poorly with the $101 billion spent worldwide on production subsidies for renewables, not to mention the counter-productive subsidies for fossil fuel energy (totalling $550 billion).[5] Effective cost reduction requires not only the wider deployment of existing clean technology but also, critically, the scientific development of new technologies.

Progress in technology is happening at an impressive pace but still not fast enough to meet the 2°C constraint with reasonable probability. The shocking underspend on renewables RD&D would matter less if the private sector were itself spending a lot on RD&D. But the energy sector does not spend heavily on RD&D. Even in the major international companies which manufacture solar and wind equipment, the ratio of R&D to sales is under 2%, compared with over 5% in consumer electronics and 15% in pharmaceuticals.[6] So a public sector initiative is vital.

Clearly there is no single magic bullet. As suggested by the IPCC, we need a number of major international research programmes. The research challenge applies to six major areas. First there are the three main types of clean energy supply: renewables (especially solar and wind), nuclear power, and coal and gas subject to carbon capture and storage (CCS). All have important roles to play, depending on the country in question. In sunny areas like India, Africa and SE Asia solar can play a central role, In more Northern areas, like Japan and Northern Europe, nuclear has an important role, as does CCS in areas rich in coal and natural gas.

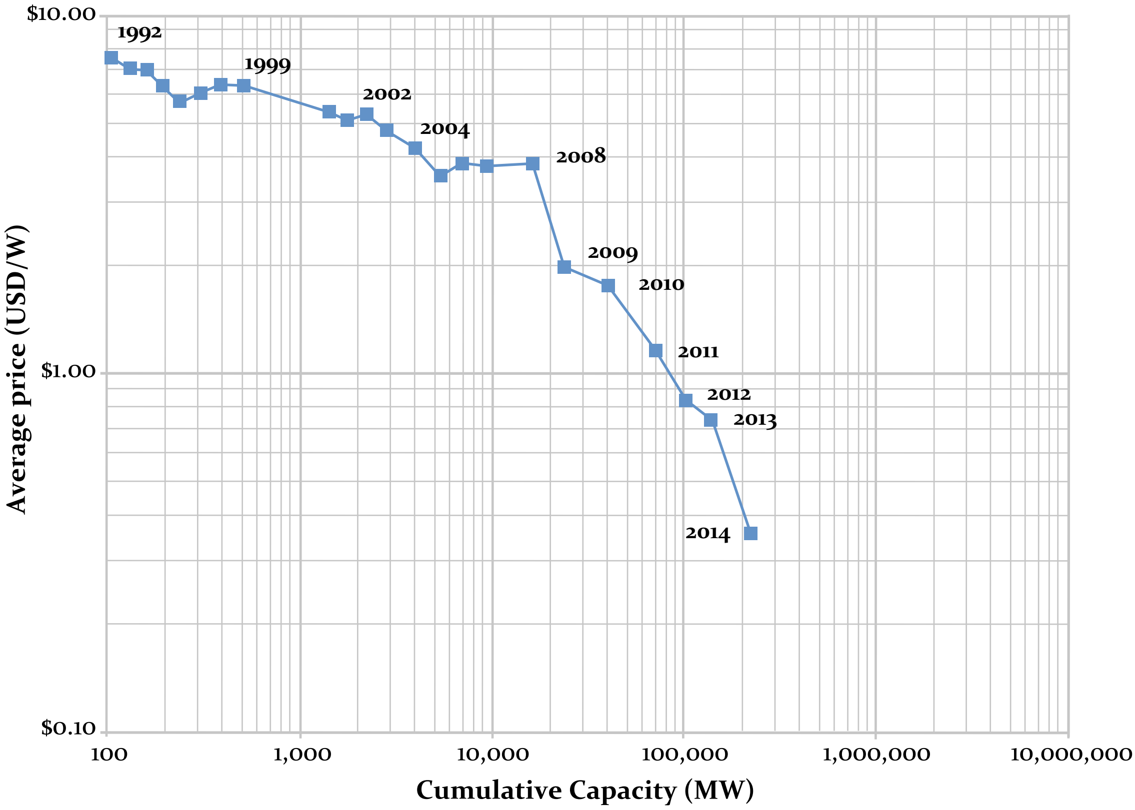
We can regard the 3 types of energy as the pillars of the system (see Figure). There are also 3 foundation elements that are common to all sources of energy. First there is our ability to store the energy cheaply for when it is needed. Then there is our ability to transmit it cheaply to where it is needed. And finally there is our ability to rein in our overall demand for energy through energy efficiency.



For three of these six areas (which are shaded in the diagram) there is already a high level of research effort. For example, in nuclear fission there is the G4 international programme to produce a much more efficient use of uranium whereby enrichment occurs on site; in nuclear fusion there is the International Thermonuclear Energy Reactor (ITER) programme. But in the three unshaded areas (renewables, storage and transmission) there is far too little research and the present proposal focusses on those areas.

There are a number of reasons for this choice. First most of the future growth in world energy demand will be in countries with high solar radiance. Second, the prices of renewable energies (especially solar power) have been falling extremely fast (see Figure). This trend can be expected to continue, but not fast enough unless supported by basic RD&D. Third, renewable energy can never replace base-load fossil-fuel powered electricity unless it can be stored more cheaply. And, finally, its integration into the grid requires more sophisticated software management.

How the price of silicon PV modules has fallen as installed capacity has risen



Electricity from renewables

The sun provides 5,000 times more energy to the earth's surface than our total human demand for energy. It is particularly abundant in the developing nations of Asia and Africa where most of the future increase in world energy demand will occur.

One method of collecting this energy is through photovoltaic (PV) panels in fields, preferably wasteland or deserts, or on roofs. These can be connected to the grid, or they can be used for local supply. The latter is especially helpful in rural areas where no grid exists, and it can be a key component in the objective of achieving Sustainable Energy for All. Prices of PV panels have been falling by 17% for every doubling of capacity.[7] But with more research they can fall even faster – as they do in consumer electronics (which, like PV, uses semiconductors). Contrary to common opinion, solar PV does not need cloudless sunlight, and for day-time use it is already approaching competitive pricing levels in places as different as Germany, California and Chile.

By contrast concentrated solar power (CSP) needs direct sunlight but this is amply available in desert areas, which are especially common in the developing world (and 90% of the whole world's population live within 3,000 km of a desert).[8] Distribution (using DC) is less costly than many people imagine, with only 3% of power being lost for every 1,000km of transmission.[9] CSP is currently more expensive than PV, but costs are falling with increased deployment.

Of all renewables, on-shore wind is now the cheapest, wherever wind is plentiful. But prices are falling more slowly and basic research is needed to restore the momentum of falling prices.

Electricity storage and smart grids

However, if renewable energy is to become the primary source of energy, it must be capable of being stored and supplied when and where it is needed. Wind is an intermittent source of energy, and sunlight is confined to the daytime, whereas winter demand peaks in hours of darkness. Moreover, electric vehicles need their energy far from where it was generated. This is a major research challenge, and cracking it will be a key to cheap and universal clean energy. Clearly the storage requirements are different for mobile vehicles, when compared with electricity for the grid or for local consumption.

One current area of breakthrough is batteries, especially those based on lithium ions, vanadium and other flow batteries. But there are also other possibilities including thermal storage, capacitors, compressed air, fuel pumps, flywheels, molten salt, pumped hydro and hydrogen.

Hydrogen has other potential uses as a source of clean energy. It may become an economic fuel for road vehicles (directly or indirectly via methanol) and it may become possible to generate it directly from sunlight by photocatalysis of suitable substances.

Finally, to use renewable energy effectively in a grid requires complex operations of balancing supply and demand. Major improvements in grid software and interconnectors are needed for an efficient system of clean electricity.

Proposals

With a really focussed 10-year Programme of RD&D beginning in 2016, it should be possible to discover the disruptive new technologies which can help produce clean energy on a massive scale before it is too late. Here we propose a Global Apollo Programme which all countries are invited to join, with the following features:

(1) **Target**. The target will be that new-build base-load energy from renewable sources becomes cheaper than new-build coal in sunny parts of the world by 2020, and worldwide from 2025.

(2) **Scale**. Any government joining the Programme consortium will pledge to spend an annual average of 0.02% of GDP as public expenditure on the Programme from 2016 to 2025. The money will be spent according to the country's own discretion. We hope all major countries will join. This is an enhanced, expanded and internationally co-ordinated version of many national programmes.

(3) **Roadmap Committee**. The Programme will generate year by year a clear roadmap of the scientific breakthroughs required at each stage to maintain the pace of cost reduction, along the lines of Moore's Law. Such an arrangement has worked extremely well in the semi-conductor field, where since the 1990s the International Technology Roadmap for Semiconductors (ITRS) has identified the scientific bottlenecks to further cost reduction and has spelt out the advances needed at the pre-competitive stages of RD&D. That Roadmap has been constructed through a consortium of major players in the industry in many countries, guided by a committee of 2-4 representatives of each main region. The RD&D needed has then been financed by governments and the private sector.

The Global Apollo Programme will follow this model. There will be a Commission consisting of one representative of each member country and, under it, a Roadmap Committee of some 20 senior technologists and businessmen who will construct and revise the roadmap year by year. It will be co-located with the International Energy Agency in Paris, but will of course include very many countries not belonging to the IEA. All results discovered through the programme will be made publicly available, though patentable intellectual property will be protected and will remain with those who made the discoveries.

We believe strongly that, in terms of value for money, this Global Apollo Programme is an essential component of any serious attempt to manage the risks of climate change. At relatively small cost it will contribute powerfully to a safer and better world. We urge the Heads of Government to agree on such a programme.

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1. THE PERILS OF OUR CURRENT COURSE

For many decades both world temperature and sea levels have been higher than in the previous decade, and this is due to man-made emissions of greenhouse gases. The average temperature is already 0.8°C above the pre-industrial level. If it rises to over 2°C above that level, there are will be serious environmental consequences for billions of people – including increased droughts, floods and storms. Millions will lose their livelihood and have to migrate, causing increased tensions and the risk of war.[10]

So the world's temperature is a classic public good – it is affected by each one of us, but the consequences of our individual decisions on energy use fall almost entirely on other people. For these reasons the nations of the world agreed at Cancun in 2010 to take collective action to limit the world rise in temperature to 2°C.

But what are the chances that this will be achieved? On present policies there is little or no chance. But, hopefully, decisions to be taken by December 2015 will change things. The purpose of this pamphlet is to suggest *one* key ingredient in that process.

To see the urgency of the situation, we need only look at the inexorable increase in the level of carbon dioxide in the atmosphere. This has risen from 270 ppm (parts per million) in the pre-industrial world to 400 ppm now, and it is now rising at over 2 ppm each year. To prevent a rise in temperature beyond 2°C (with 50% probability) requires that we halt the rise in the stock of carbon dioxide before it reaches 450 ppm. This requires a drastic reduction in the net flow of new carbon dioxide into the atmosphere from now on.

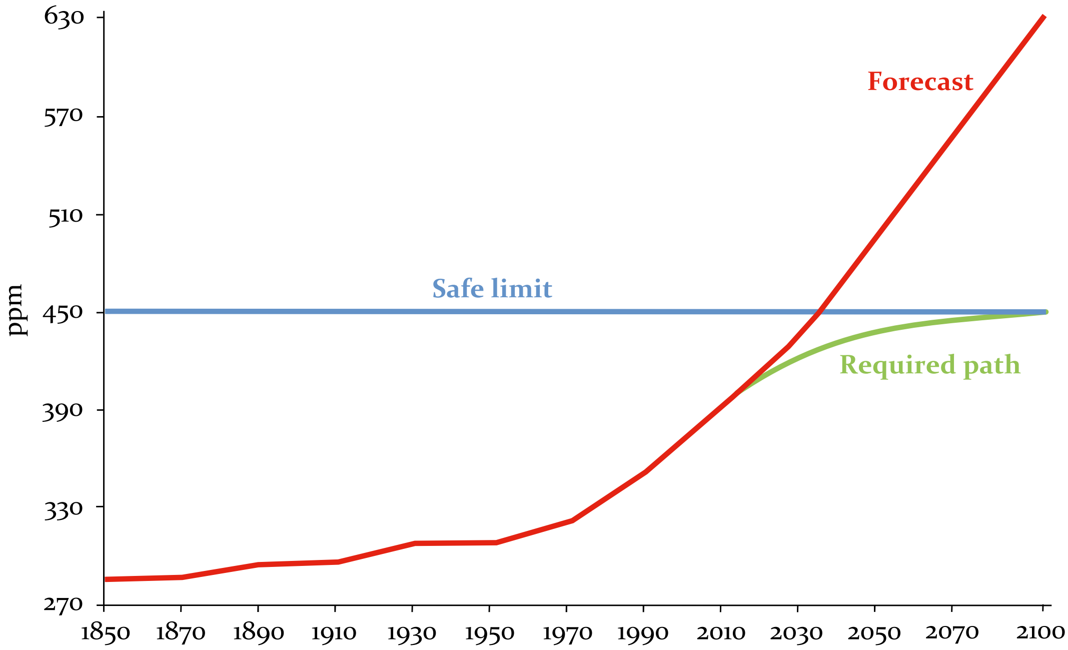
Will it happen? Most forces are working the opposite direction. By 2035 world population will have grown by 25%, and income per head will have more than doubled. So, even if there are major improvements in energy efficiency (which there will be), total energy demand will rise by 33% by 2035, and even more thereafter.[11]

Suppose we take the most favourable interpretation of all the promises which governments worldwide have made so far. The average forecast is that we will pass the critical 450 ppm level around 2035, and by the end of the century we will reach 630 ppm (see Figure 1).[12] On the central forecast this will raise world temperatures by 4°C, with massive implications including the melting of permafrost and major rises in sea-level.

The forecast is of course subject to great uncertainty, with a 50% probability of even higher temperatures. To avoid these risks is a matter of simple common sense. The world needs to insure itself, by taking evasive action.

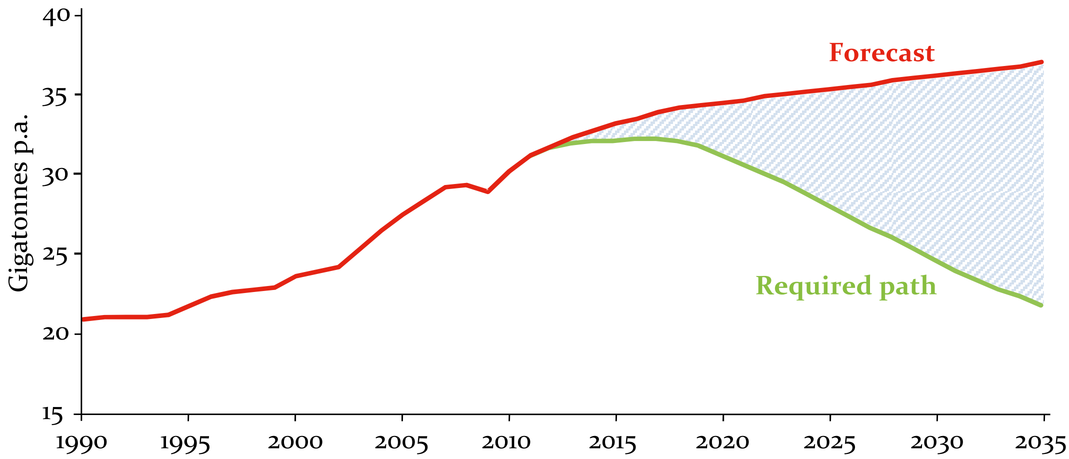
To stop the carbon dioxide concentration reaching 450 ppm, we need to cut emissions drastically and to cut them very soon. Within decades we need to reduce them to virtually zero (see the green line in Figure 1).

Figure 1: Atmospheric concentration of CO2



The International Energy Agency (IEA) have helpfully proposed a time path for this up to 2035.[13] This is shown as the lower line in Figure 2.[14] The contrast with what is currently forecast is striking. Moreover the forecast itself is probably over-optimistic about what will actually happen. It includes all commitments which have been announced, whether or not they appear credible. For example, it assumes that all fossil fuel subsidies will be phased out within ten years (except in net exporting countries), and that carbon pricing, which now covers 8% of world emissions, will instead cover 33%. So by 2035 emissions will have to be cut by at least 40% compared with what would otherwise happen.

Figure 2: Energy-related CO_2 emissions



To do this will require the whole range of policy changes proposed by the IPCC and the IEA.[15] These include measures to improve energy efficiency (and thus reduce energy demand) as well as measures to shift the supply of energy from fossil to non-fossil fuel sources. The need here is urgent, both to control CO_2 and to ensure that money is not wasted on fossil investments which then become uncompetitive.

The world demand for energy is divided roughly equally between buildings (heating, cooling, lighting, cooking, appliances); industry; and transport (mainly road vehicles). So, to reduce energy demand, there need to be tough regulations on buildings, industry and vehicles and on the use of waste. To change the pattern of energy supply, we need carbon pricing as well as feed-in tariffs for renewables, both of which encourage their supply. But in addition the IPCC and the IEA stress the importance of RD&D to reduce the cost of renewable energy.[16] This means the application of basic science to produce fundamental disruptive technical change of the kind we have seen in telecommunications and IT. Those revolutions all began with publicly supported RD&D.[17] So how has the world been doing in terms of public support for clean energy RD&D?

2. THE DANGEROUS SHORTFALL IN RD&D

The answer is totally astonishing. We are talking about the greatest material challenge facing humankind. Yet the share of global publicly-funded RD&D going on renewable energy worldwide is under 2% (see Table 1).[18 19] Remarkably the share of all energy research in total publicly-funded R&D expenditure has fallen from 11% in the early 1980s to 4% today. This is a shocking failure by those who allocate the money for R&D.

Table 1: Global public spending on low-carbon energy RD&D (latest year)

	$ billion		As % of total public spending on R&D
Renewables:			
Solar and wind	3.2		
Vehicles (incl. hydrogen)	1.7		
Storage and transmission	1.0		
Total		5.9	1.8%
Bioenergy		1.3	
Nuclear fission		4.2	
Energy efficiency		2.1	
Carbon capture and storage		1.3	

It might not be so serious if the private sector were doing a great deal of RD&D itself. But the energy sector is one of the least research intensive of all sectors. Even in the major international companies which manufacture PV and wind equipment, the ratio of R&D to sales is under 2%, compared with over 5% in consumer electronics and 15% in pharmaceuticals.[20] It is not surprising that 10 out of the 16 major advances in PV efficiency can be traced back to government and university research and development programmes.[21]

So what is going on? Policy-makers have been relying on the private sector to solve the problem, with governments simply creating a favourable market for clean energy. There have been major subsidy payments for the supply of renewables amounting to $101 billion a year in 2012.[22] But at the same time public expenditure on R&D to reduce the cost of renewables has been minimal - some $6 billion. This cannot be a sensible balance of support. In Europe the position is similar to elsewhere: the ratio of public R&D to public subsidies for the supply of existing renewables has been roughly 1:30.[23]

At the same time, fossil fuel is getting a subsidy of at least $544 billion worldwide – making climate change worse, not better.[24] As the figures in Table 2 show, there is neither rhyme nor reason behind current policies in this area.

Table 2: Some striking numbers

	$ billion p.a.
Govt R&D expenditure (OECD):	
Total	333
On renewables	6
Subsidies:	
to renewables	101
to fossil fuel	544
Official development aid (OECD)	127
Promised public and private payments by rich countries to developing countries for climate change mitigation	100

The case for greater RD&D on climate change is doubly powerful because there are two types of public good involved. The first is climate change (a public bad, justifying public outlays to mitigate it). The second is R&D in general, where the potential gains to society always exceed the potential gains to the agent undertaking the R&D. R&D in the energy sector will have huge spillovers in that sector but also in other domains beyond the power sector, such as solar cells and small efficient batteries which will power all kinds of new consumer electronics and wearable computing.[25] Nor can the health benefits be underestimated: pollution and coal-mining fatalities in the emerging countries, such as China and India, are continuing problems from fossil fuel usage.[26] Thus there is a double-whammy case for more public expenditure on RD&D that is targeted at climate change.

Moreover such a Programme should be international since all countries will gain. What form should such a Programme take? Should it have any particular focus? There are two powerful arguments for a degree of focus. First, if one broad area looks the most promising, there may be returns to scale from a concentrated use of funds. But, second, extra funds are unlikely to be forthcoming at all unless there is a focus which strikes the imagination of policy-makers and of the general public. Both arguments point to a heavy focus on solar energy and on electricity storage, which is relevant to all types of renewable electricity.

3. SOLAR ELECTRICITY [27]

The proposed Programme has one aim only – to develop renewable energy supplies that are cheaper than those from fossil fuels. There are already very important examples of this, such as hydropower and geothermal energy, but these are often limited due to geography, environmental concerns and financing difficulties, and they don't scale across the planet. Wind and solar are already competitive in some parts of the world, but intermittency reduces extensive use. Solar in particular is competitive for the thousands of villages in India and Africa which are off-grid. At present most renewable energy in most parts of the world, however, are more expensive than energy from fossil fuels, and it only becomes economic due to subsidies or feed-in tariffs. But eventually these subsidies have to stop. So we are looking for the technologies with the greatest potential for falls in cost year after year, on a global scale. In addition, the materials used should not be constrained in supply nor toxic, the risks of price volatility should be low, and the installation payback period should be short.

Price trends

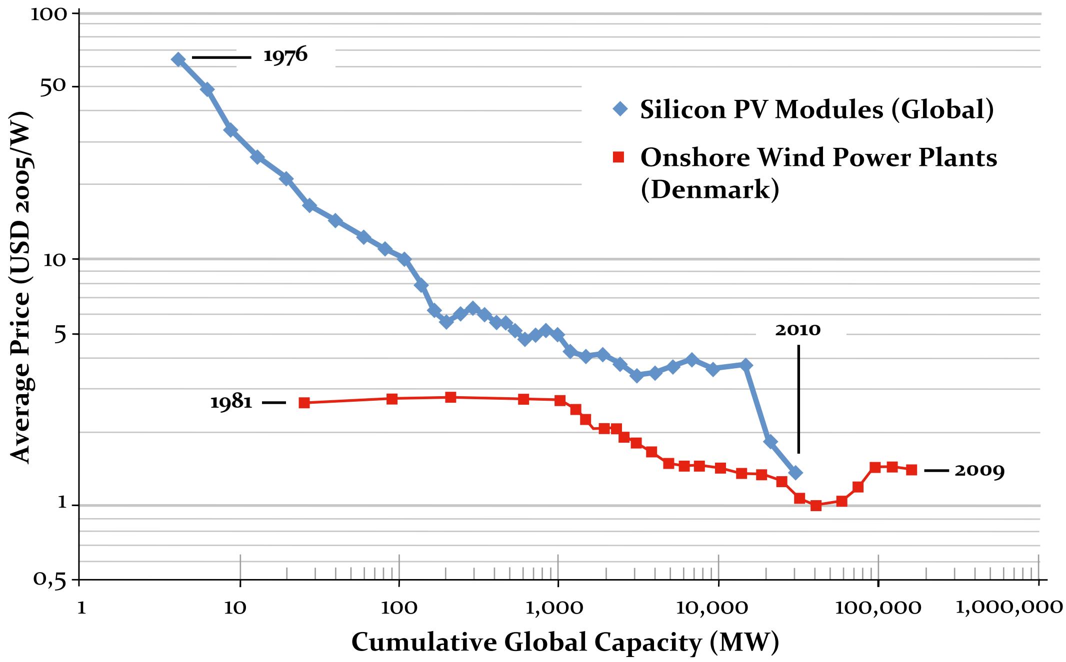
A key parameter here is the 'learning rate' – the rate at which the price of the equipment falls as the installed capacity increases. Photovoltaic solar electricity (see box) has seen a very high rate of price fall with increasing output volume.[28] This is because it depends on semiconductor materials – as do consumer electronics, where the price falls have been even more sensational. Concentrated solar power (see box) also has shown a steep learning curve.

Table 3 gives the learning rates which the IEA expect for some decades to come. The logic of compound interest here is compelling. The IEA believe that photo-voltaic panels will eventually reach a floor price, but new truly disruptive technologies, such as plastic photovoltaics, could continue the downward fall in price. The price of wind has also fallen with increased capacity but somewhat less sharply, as Figure 3 shows. These price trends help to create a prima facie case in favour of focussing heavily on solar energy. If fundamental breakthroughs are added to learning by doing, the combination can produce even more rapid falls in cost – exactly as has happened in consumer electronics.

Table 3: Expected learning rate i.e. fall in price for each doubling of capacity

(Flat panel electronic displays)	(35%)
Solar (photo-voltaic)	17%
Solar (concentrated solar power)	10%
Wind offshore	9%
Wind onshore	7%
Biomass	5%
Geothermal	5%
Hydro	1%

Figure 3: How price has fallen as installed capacity has risen



PHOTOVOLTAIC ELECTRICITY (PV)

A photovoltaic cell is a semiconductor device that enables photons to "knock" electrons out of a molecular lattice. This leaves a freed electron plus a corresponding hole, which together set up a direct electrical current. Most PV cells are currently made of silicon. These PV cells are then combined to form a unit for delivering electricity. Panels can be mounted in fields (as small power stations, as in this photo), or on roofs or walls. In fields the orientation of the panels can be fixed, or moveable to track the movement of the sun.

The electricity can be locally consumed or fed into the grid – with power ranging from a few watts to millions of watts. Normally the electricity is transformed to AC and the cost needs to allow for this and the many other costs involved in mounting the cells and incorporating the resulting electricity into the delivery system.

Image: U.S. federal government.

CONCENTRATED SOLAR POWER (CSP)

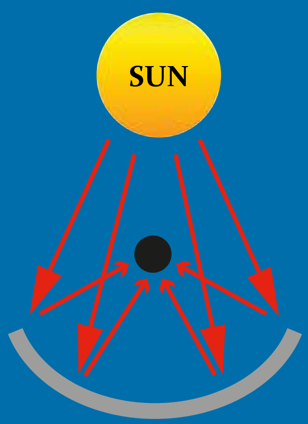
Concentrated solar power uses mirrors to concentrate the rays of the sun on a single point, thereby generating temperatures of up to 1000°C. The heat produced is held in a suitable material, like a molten salt, and is then used as needed to heat steam, which drives a turbine, generating electricity.

The advantage is that the heat can be stored overnight and used as needed. The disadvantage is that only direct sunlight (without cloud) can be used. One way to deal with the problem of intermittency is a hybrid plant which generates the steam by solar power when solar power is available but otherwise by coal or gas.

There are many designs for concentrating the sun's rays, of which the simplest is the trough (illustrated below) where sunlight is focussed on a pipe carrying oil or some other heat-carrying medium. Other designs involve towers (see below). In each case the focussing mechanism moves to track the movement of the sun.

Like PV, CSP can also be used to some extent to balance wind power, since the wind blows more when the sun is in cloud.

A TROUGH



THE TOWER AT GEMASOLAR (SPAIN)

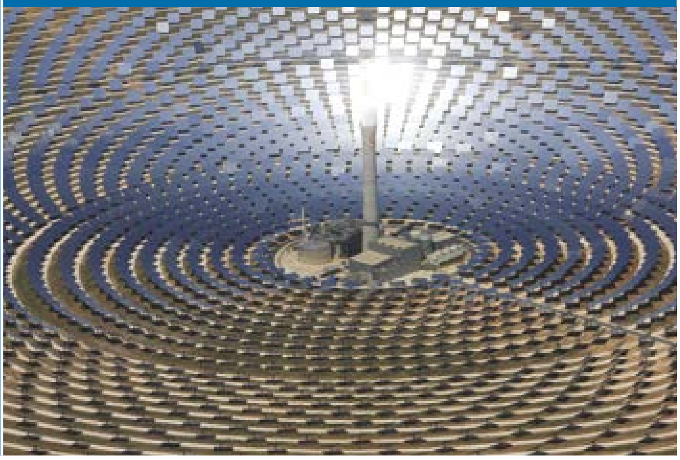


Image: The Global Federation For Sustainable Development.

Availability

There are however many other elements in the case for solar energy. The energy which falls on the earth from the sun is 5,000 times the total energy we use in the world for all purposes. Though the irradiance (or solar flux) is greater at the tropics than elsewhere, it is very substantial in temperate climates, even when there is cloud. This is shown in Figure 4. Irradiance in Chicago is near to 50% of that in the Sahara. And for photovoltaic electricity it is irradiance which matters, rather than direct sunlight (without cloud).

By contrast, concentrated solar power needs direct sunlight and this is much more plentiful in developing nations. Almost all the growth in world energy demand in the coming decades will be coming from Asia, Africa and Latin America – the very countries where sunlight is most abundant (see Figure 5).

Figure 4: The solar flux at the earth's surface over the year

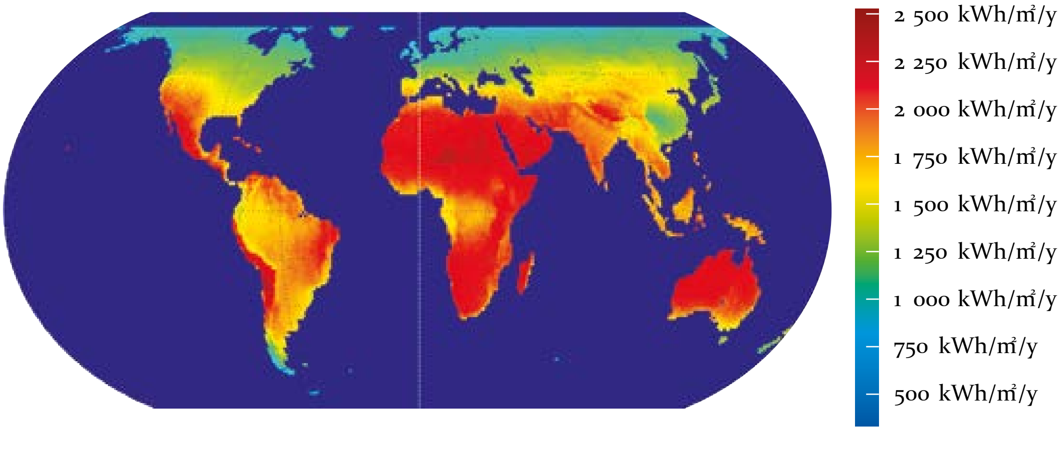
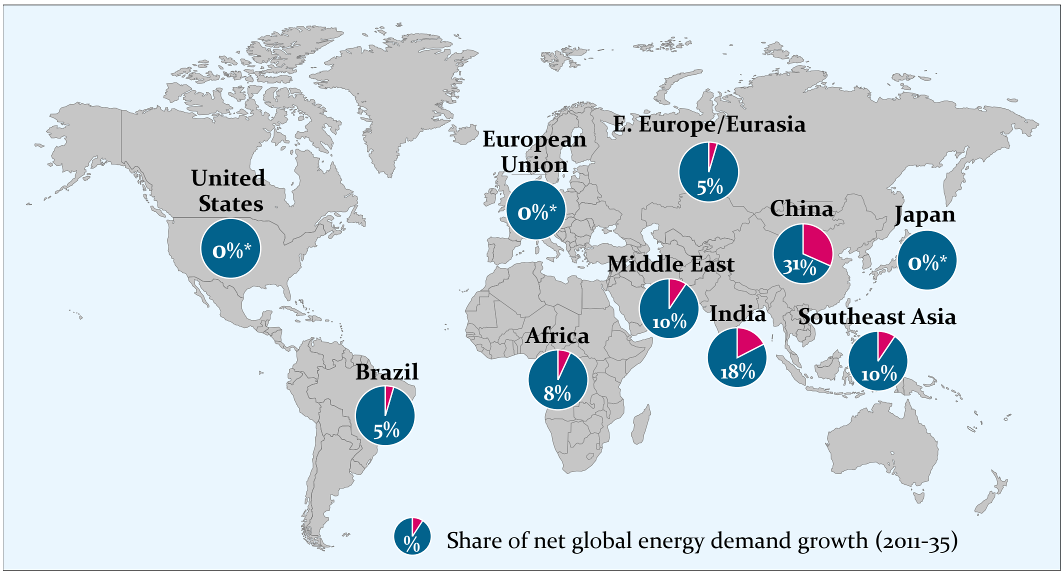


Figure 5: Shares in the global growth in energy demand



Moreover in those less-developed countries grids are often less complete. There is therefore a huge advantage in having a source of energy that is universal and can be tapped near where it is used. PV power is the most obvious of these. Photovoltaic electricity can be produced at any scale and much of it can be mounted on buildings, thereby reducing the land area used for producing energy.

Concentrated solar power is also best suited to sunny areas. Desert areas without cloud are best of all for this purpose. Some 90% of the world's population live within 3,000 km of a desert area, and some 1% of the worlds' desert area would be sufficient to supply the world's energy needs.[29] There is of course a cost of transmission, which is mainly the cost of building the new grid. The actual losses of electricity in transmission at high voltage direct current (HVDC) are now quite small – some 3% for every 1,000 km plus 0.6% due to conversion between DC and AC at both ends of the line.[30] This is a key new development.

The Indian sub-continent and China are well supplied with deserts. Both India (in the Rajasthan Desert) and China (in the Gobi Desert) have major solar projects in deserts, with well over 1GW capacity each. There are also desert areas in richer parts of the world like South-Western USA, Spain, and North Africa. Much of Europe's energy needs could be supplied from solar electricity generated in Spain, if grid hardware and software were adequate. In addition the Desertec Industrial Initiative aims by 2050 to use power generated in deserts near to the Mediterranean to supply most of the energy needs of the Middle East and North Africa and 15% of Europe's electricity (by power lines passing under the sea).

4. ELECTRICITY STORAGE

But a major problem with solar and wind energy is intermittency. The timing of solar flux may be easier to forecast than of wind, but at night time there is no light. Thus, if renewable energy were to supply base load electricity, it would have to be stored and some of it would need to be stored for some months to meet the peak demand in winter. This would add to the cost. So there is an urgent need to develop better ways to store electricity. Better storage will also make nuclear power more effective since nuclear production is not variable and needs to be storeable where there is short-run oversupply.

On intermittency of supply, we can distinguish five time-frames, each requiring a different solution:

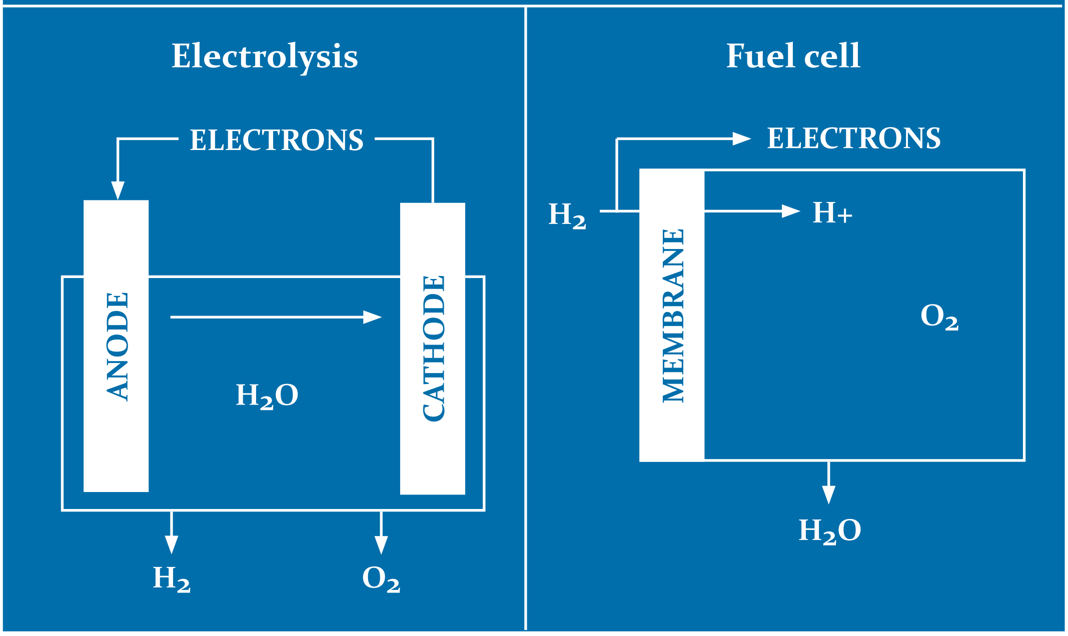
- minute by minute fluctuations in voltage or frequency, which require small amounts of storage;
- backup for a power source failure or for the sun being obscured;
- a time shift of 4 to 6 hours from sunlight to hours of darkness;
- storage over a week or so to allow for windless days or long storms;
- longer timescales, eg storage from summer to winter.

There are many possible ways of storing electricity.

- **Batteries**. This is one of the most promising areas, especially lithium-ion and flow batteries. If the batteries are for storing grid electricity, they can of course be large. But if they are to power electric vehicles, weight becomes a major issue.
- **Thermal storage**, eg in water, buildings, the ground or molten salt.[31] This is economic for a 4-6 hour time-shift.
- **Pumped hydro**. The standard way of storing electricity (from whatever source) has been pumped hydro. Electricity pumps water up to a reservoir and, when the electricity is needed by the public, the water is released to drive a turbo-generator. The overall loss of power is some 20%[32] but this is one of the best methods for inter-seasonal storage.
- **Capacitors**. These are materials (like natural amber) capable of holding an electric charge. More research could well produce breakthroughs, applicable to short time-frames.
- **Compressed air**. Energy is used to compress air and is recovered when the air is released to drive a turbine.
- **Flywheel**. Energy accelerates the flywheel, and can be recovered by slowing the flywheel.

- **Hydrogen**. Hydrogen can act as a storage medium for electricity. An electric current (however produced) can be used to electrolyse water to produce hydrogen and oxygen. Then, when the electricity is actually needed, the operation can be reversed in a "fuel cell". In this cell hydrogen is passed through a membrane to combine with oxygen, producing water – but the spare electrons pass outside the membrane to produce electric current (see box). This electricity can then be used as ordinary grid electricity, or it can be used to power an electric vehicle.

GETTING HYDROGEN BY ELECTROLYSIS AND THEN USING IT IN A FUEL CELL TO PRODUCE ELECTRICITY



In road transport it is of course crucial that we find ways to replace oil by electricity. As we have seen one way is through batteries. The automobile industry is already investing heavily in rechargeable lithium ion batteries and in the use of hybrid vehicles, which use braking power to recharge their batteries.

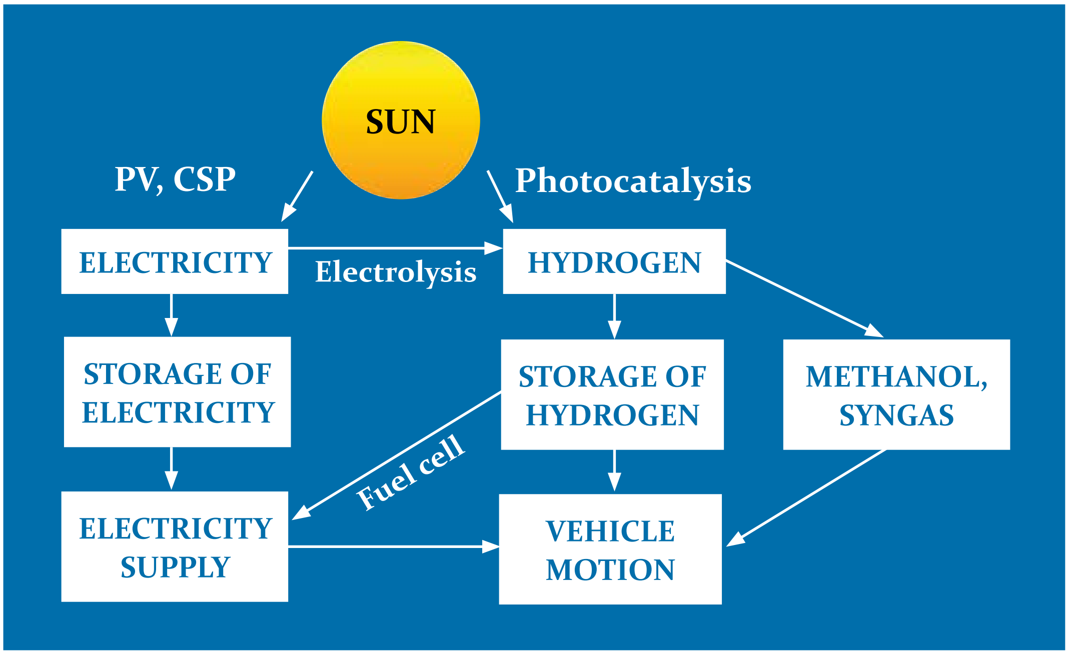
But an alternative storage system uses hydrogen, which has many potential uses in the area of transport.

(i) Hydrogen can be used to power electric vehicles directly using **fuel cells**. Cost reductions will need a reduction in the platinum loading of the cell membranes.

(ii) Hydrogen can be used directly as the fuel for an **internal combustion engine**, where it explodes, combining with oxygen to produce water.

(iii) Hydrogen can be combined with atmospheric CO_2 to produce **chemical fuels** like methanol from which to produce petroleum. (Or it can simply be mixed with other gases to produce syngas.)

So there are many potential ways in which we can use the sun and wind to power the world economy. Almost all these ways require more research to become fully competitive. The box shows some of the key links which require further research.



5. PRIORITIES FOR RD&D

It would be for the Programme to select its own research priorities. But some obvious examples include the following.[33]

1. The generation of electricity

There is still potential for major cost-reductions in PV. The dominant current technology is silicon but there may be major possibilities using thin film, compound semiconductors, plastics or dye-sensitised materials. Incorporation into existing building materials and a reduction of so-called balance-of-system components that make up 70% of the cost today, are also major issues. There may also be scope for cheap non-rotating CSP structures at lower temperatures, to produce chemical fuels.

2. The storage of electricity

This should be central to the programme. Batteries and capacitors need major research, as does hydrogen, and control systems for re-extracting energy from thermal storage.

3. The storage of hydrogen

This can be as gas or liquid. Or it can be held in a solid compound, which releases hydrogen when heated and can then reabsorb hydrogen when it needs replenishing. (This technology is used to power German submarines.)

4. Smart grids

A major obstacle in the deployment of renewables beyond 30% of grid power is the integration into the grid. This requires high-grade software and better interconnectors. There are also major issues of regulation which require sophisticated economic analysis.

To conclude, renewables have enormous potential for price reduction. They are not yet cost-competitive in most parts of the world (see Annex) but are moving in that direction. But we cannot just wait for that to happen. There is an overwhelming case for a major research effort to ensure that it happens, and happens as fast as possible.

6. THE GLOBAL APOLLO PROGRAMME

So what scale of research programme would be justified? A possible starting point for the discussion is the original Apollo Programme (which was mainly concentrated in the 10 years 1960-69). That Programme cost about $150 billion in today's dollars if we update the original cost by the increased cost of goods and services. But if we update the cost by the price of scientists it comes to considerably more.

So we consider $15 billion a minimum acceptable scale for the Programme in its early years, rising thereafter in line with GDP growth.[34] This would amount to 0.02% of world GDP. It would be only 4% of overall RD&D - surely a minimum spend on the world's greatest technological problem.

The proposed programme will operate as follows.

1. **Target.** The programme will have a clear target, just as the original Apollo Programme had. The target will be that new-build base-load energy from renewable sources becomes cheaper than new-build coal in sunny parts of the world by 2020, and worldwide from 2025.

2. **Scale**. Any government joining the Programme consortium will pledge to spend an annual average of 0.02% of GDP as public expenditure on the Programme from 2016 to 2025. The money will be spent according to the country's own discretion but the Programme would proceed even if not all countries joined. We hope all major countries will join. This is an enhanced, expanded and international version of many national programmes.

3. **Roadmap Committee**. The Programme will generate year by year a clear roadmap of the scientific breakthroughs required at each stage to maintain the pace of cost reduction, along the lines of Moore's Law. Such an arrangement has worked extremely well in the semi-conductor field, where since the 1990s the International Technology Roadmap for Semiconductors (ITRS) has identified the scientific bottlenecks to further cost reduction and has spelt out the advances needed at the pre-competitive stages of RD&D. That Roadmap has been constructed through a consortium of major players in the industry in many countries, guided by a committee of 2-4 representatives of each main region. The RD&D needed has then been financed by governments and the private sector.

The Global Apollo Programme will follow this model. There will be a Commission consisting of one representative of each member country and, under it, a Roadmap Committee of some 20 senior technologists and businessmen who will construct and revise the roadmap year by year. It will be co-located with the International Energy Agency in Paris, but will of course include very many countries not belonging to the IEA. All results discovered through the programme will be made publicly available, though patentable intellectual property will be protected and will remain with those who made the discoveries.

The whole world faces a massive challenge, which only science and technology can solve. We urge the Heads of Government to agree on a Global Apollo Programme by the Paris meeting in 2015. The Programme should begin immediately after that. By harnessing the power of the sun and wind in time, we have a good chance of preserving life on earth as we know it. Unlike fossil fuel, they produce no pollution, and no miners get killed. Unlike nuclear fission, they produce no radioactive waste.

We are talking about a crisis more serious than most major wars. This is the biggest scientific challenge of the 21st century. Let us show we have the collective intelligence to understand and overcome the danger that faces us.

ANNEX

How competitive is renewable energy?

The standard way of comparing the cost of different types of electricity is to look at the levelised cost of electricity (LCOE) per MWh. In the following calculation by Bloomberg New Energy Finance and the World Energy Council, it is assumed that investors require a 10% real rate of return. Combining this with assumptions about the cost of capital investment per MW, the utilisation rate of the capital, and the costs of fuel, operations and maintenance, it is possible to calculate the price that would need to be charged (in 2014 US $) for the investment to break even. (In this calculation the cost of renewables does <u>not</u> cover the whole cost of supply which should also include the cost of grid connection and the costs of accommodating intermittence which requires additional backup, never fully used.)

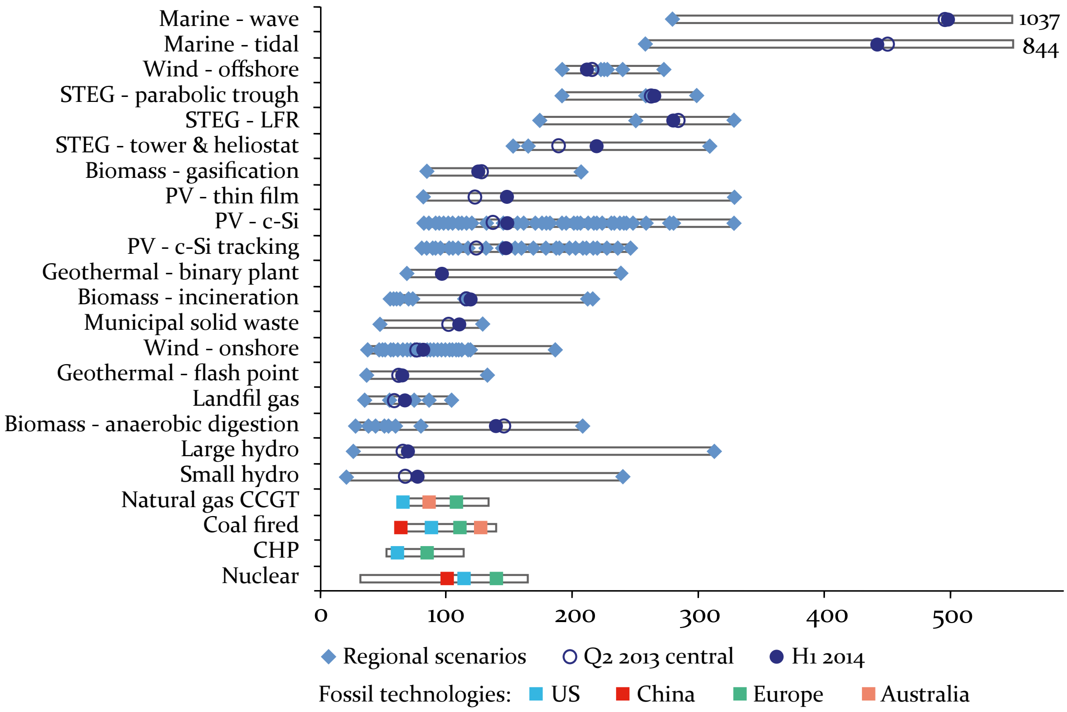
Clearly this price will differ widely between locations. Figure A1 shows calculations for all types of energy in a wide range of locations.[35] A wide range of technologies have costs centred below $100 per MWh (or 10 cents per KWh). These include onshore wind, hydro, gas and coal. At somewhat over $100 per MWh come nuclear, PV and biomass. If we focus on PV, wind and coal, Table A1 gives comparable figures for a number of countries. This makes it clear that onshore wind is not yet fully competitive, and PV less so. That both are actually being supplied is mainly due to subsidies or regulations of various kinds.

However trends are also important. The price of PV is falling sharply as Figure A2 shows. It is forecast to continue falling. Thus by 2030 it will be relatively cheaper than coal and gas with a carbon price applied (see Figure A3). The same is true of onshore wind (see Figure A4).

These are the factors which will affect the pattern of investment. Thus Bloomberg's middle forecast of new-build energy capacity suggests that the bulk of additional capacity for power generation from now on will be in renewables (solar or wind) or hydro (see Table A2). But even this is not enough in terms of its impact on the total sources of electricity supply, which by 2030 will remain very largely based on fossil fuel. This is shown in Table A3, which implies an increased output of CO_2 rather than the radical fall which is required.

This reinforces the need for renewables to expand beyond just contributing to additional capacity. They have to displace a significant fraction of the existing fossil-fuel-based capacity. This requires more radical falls in their cost of production.

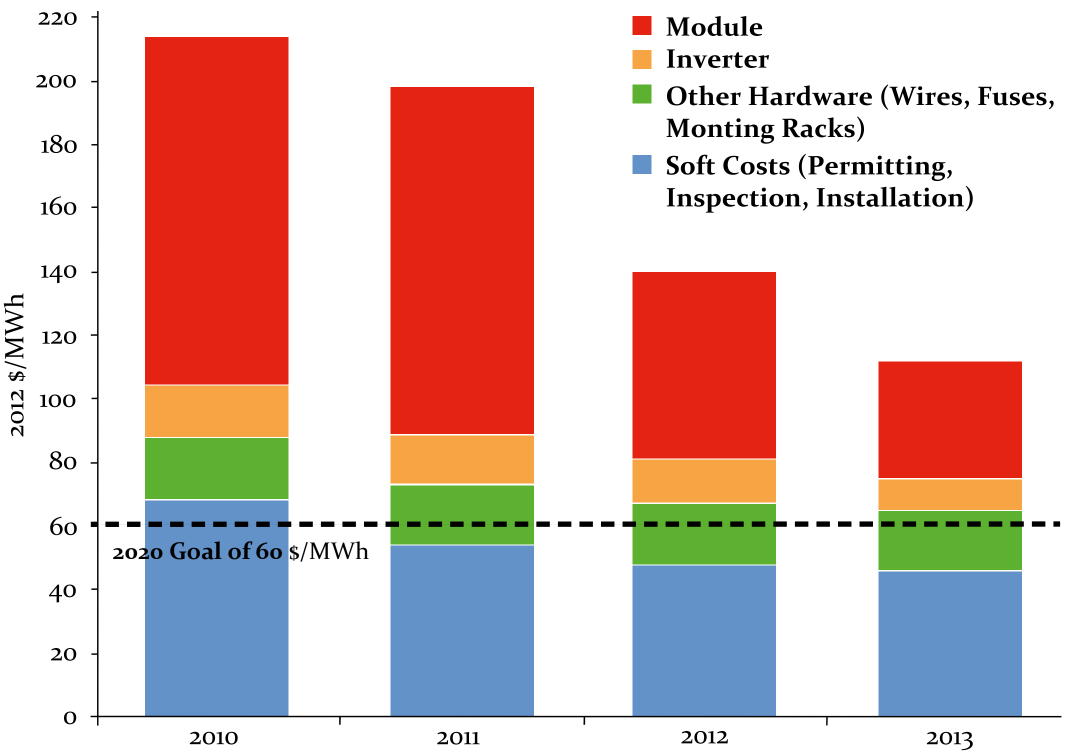
Figure A1: Levelised cost of electricity ($/MWh)



Note: LCOEs for coal and CCGTs in Europe and Australia assume a carbon price of $20/t. No carbon prices are assumed for China and the US.

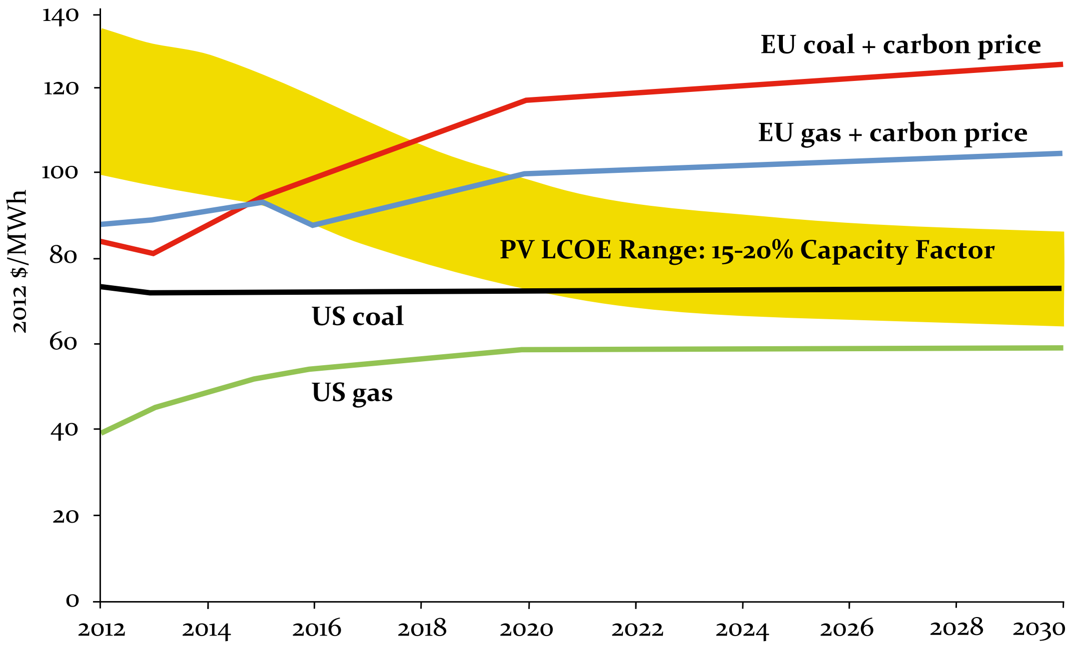
Source: Bloomberg New Energy Finance (2014).

Figure A2: Levelised cost of electricity for Utility-Scale PV Projects



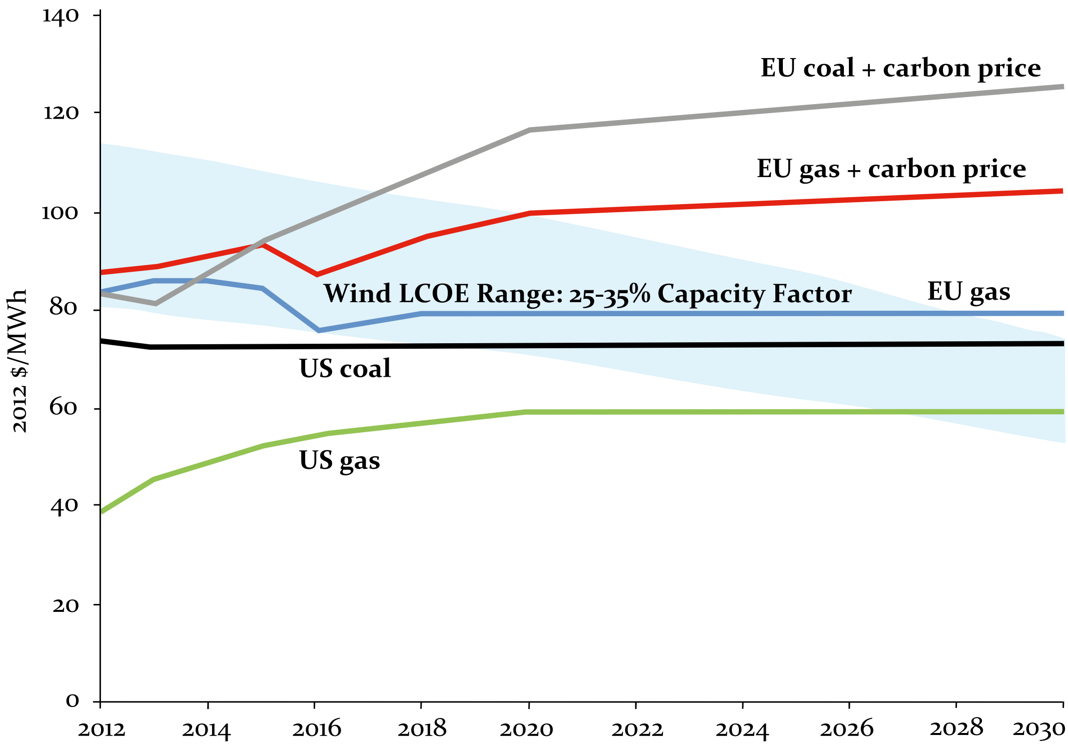
Source: US Department of Energy/National Renewable Energy Laboratory.

Figure A3: Levelised cost of electricity from PV, coal and gas – 2012-2030



Source: Bloomberg New Energy Finance (2013).

Figure A4: Levelised cost of electricity from wind, coal and gas: 2012-2030



Source: Bloomberg New Energy Finance (2013).

Table A1: Levelised cost of electricity by country and energy source

	Solar PV (c-Si)	Onshore wind	Coal
China	79-145	49-93	35-39
India	87-137	47-113	
Spain	109		
USA	117-239	61-136	77-78
Australia	127-191	71-99	93-126
Germany	226	79-82	

Source: World Energy Council (WEC) (2013).

Table A2: Composition of new electricity generation capacity (2012-2030) (%)

Solar PV	29
Onshore wind	24
Offshore wind	3
Biomass	2
Hydro	10
Nuclear	6
Oil	3
Gas	9
Coal	12
Other	2
Total	**100**

Source: Bloomberg New Energy Finance (2013).

Table A3: Composition of electrical energy produced (2012 and 2030) (%)

	2012	2030
Solar PV	-	5
Onshore wind	3	9
Biomass	3	4
Hydro	16	15
Nuclear	13	13
Gas	18	15
Coal	46	35
Other	1	4
Total	**100**	**100**
Volume of production	**20,725 TWh**	**34,170 TWh**

Source: Bloomberg New Energy Finance (2013). Note that the combined forecast here for solar and wind is in line with IEA (2013c), Table 6.1. forecast for 2035. (New Policies Scenario).

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SOURCES TO FIGURES AND TABLES

Page 3: Energy-related CO_2 emissions

IEA (2013a), Fig 1.16., p.34, modified by the authors.

Page 6: How the price of silicon PV modules has fallen as installed capacity has risen

Wikipedia http://en.wikipedia.org/wiki/Swanson%27s_law

Figure 1: Atmospheric concentration of CO_2

Stern (2007), p.5 plus IEA (2013c), p.79, adjusted to CO_2 only.

Figure 2: Energy-related CO_2 emissions

IEA (2013a), Fig 1.16., p.34, modified by the authors.

Figure 3: How price has fallen as installed capacity has risen

IPCC, SRREN SPM (2011).

Figure 4: The solar flux at the earth's surface over the year

IEA (2011), Fig 2.7, p.38 and Breyer and Schmid (2010).

Figure 5: Shares in the global growth in energy demand

IEA (2013c), Fig 2.7, p.67, modified by the authors.

Table 1: Global public spending on low-carbon energy RD&D (latest year)

IEA Data Services http://wds.iea.org/wds. Latest year - mainly 2013. The figures are for OECD countries but as Kempener et al.(2010) show publicly-financed research elsewhere adds little to the total.

Table 2: Some striking numbers

RD&D: Data for 2013. Table 1 (above) and OECD database on R&D total.

Subsidies: Data for 2012. IEA (2013c), p.93-5. IMF estimates are similar. Subsidies are measured as the difference between true cost and what users or suppliers pay. True cost does not include the 'cost of carbon'.

Development aid: Data for 2012. OECD Aid Statistics.

Table 3: Expected learning rate i.e. fall in price for each doubling of capacity

IEA (2011), p.113.

Table 4: The world in 2060. Shares in world energy supply

IEA (2011), Fig. 11.9.

ENDNOTES

[1] In conversation with Henry Ford and Harvey Firestone (Newton (1987)).

[2] IPCC (2014b) and IEA (2015).

[3] IEA Data Services http://wds.iea.org/wds. Latest year - mainly 2013. The figures are for OECD countries but as Kempener et al.(2010) show publicly-financed research elsewhere adds little to the total.

[4] See also IEA (2013b), Tables 5.2 and Figure 5.3.

[5] IEA (2013c), p.95.

[6] Laleman and Albrecht (2012), p.3. See also Grubb et al. (2014), p.321.

[7] IEA (2011), p.113.

[8] DESERTEC Foundation.

[9] IEA (2011), p.58.

[10] IPCC (2013) and IPCC (2014a). See also Stern (2007, 2013); Walker and King (2008). However, some people argue as follows. Much of the future problem arises since we shall be much richer then. So why should we worry if greenhouse gases slightly reduce our future income. This argument is fallacious because it ignores distributional issues, it assumes that income is an adequate measure of wellbeing, and it exaggerates the cost of action now to avert climate change.

[11] IEA (2013c). See also note 2.

[12] IEA (2013c), p.79 adjusted to CO_2 only.

[13] This is very similar to the lowest of the IPCC's Representative Concentration Pathways, see Schaeffer and van Vuuren (2012), Fig. 2.

[14] A gigatonne is 10^9 tonnes

[15] See IPCC (2014 a and b) and IEA (2013c), p.52

[16] This is on top of the cost-reductions which come from learning-by-doing and economies of scale – see Zachmann et al. (2014).

[17] The fundamental research which produced the semiconductor chip and the internet was funded by the US Defense Department (DARPA) and that which produced the worldwide web was funded by CERN. Other major innovations which originated in publicly funded research are the computer, nuclear power, satellite communications (from the Apollo Programme), miniaturisation (likewise) and broadband (in South Korea). See also Mazzucato's 'The Entrepreneurial State, e.g. http://www.demos.co.uk/Entrepreneurial_State_web.pdf.

[18] See endnote 3.

[19] See endnote 4.

[20] Laleman and Albrecht (2012), p.3. See also Grubb et al. (2014), p.321.

[21] IEA (2011), p.112. See also IEA (2013b), p.18, which reports that 13 out of 14 top PV innovations in the US since 1980 were developed with government support.

[22] IEA (2013c), p.95.

[23] Laleman and Albrecht (2012). See also Zachman et al. (2014) who quote a ratio for the five largest European countries in 2010 of £350 million to £48 billion.

[24] IEA (2013c), p.93. The IMF give a higher figure which includes as a subsidy the absence of a proper carbon tax – see IMF (2014).

[25] For evidence that clean energy research has bigger research spillovers (citations) than dirty energy research, see Dechezleprêtre et al. (2013). The case for the Programme is based on its <u>overall</u> spillovers, including its effect in reducing CO_2 emissions.

[26] Pandey et al. (2006).

[27] For an excellent treatise on solar energy, see IEA (2011). See also *Philosophical Transactions of the Royal Society*, 371(1996): August 2013, and Proceedings of the IEEE, 100(2): February 2012.

[28] The fall in the price of PV is not mainly due to Chinese dumping of goods at prices below cost.

[29] DESERTEC Foundation.

[30] IEA (2011), p.58.

[31] Molten salt is 95% efficient for short-term storage, see IEA (2011), p.149.

[32] IEA (2011), p.150.

[33] We have not included direct solar heating as there are fewer basic research issues here.

[34] The IEA's central estimate of the RD&D gap is $16-36 billion for solar plus electric/hydrogen vehicles (though in their estimate vehicles predominate), see IEA (2013a), Table 5.2.

[35] The basic unit of power is the watt and the basic unit of work (or energy) is the amount of work done by one watt in one second. (One watt-second is otherwise known as one joule).

The power of an electricity system is often measured in gigawatts (1GW = 109W) or megawatts (1MW = 106W), or kilowatts (1kW = 103W). A typical large power station might be 1GW in size and a small electric toaster 1kW.

The work done by electricity is often measured in kilowatt-hours (1kWh = 103Wh) or at national level in terawatt-hours (1TWh = 1012Wh). A 1GW power plant working year round produces 8.8 TWh. Another unit for measuring work done is a million tons of oil equivalent (Mtoe) which equals 11.63 TWh. (Note also that Watts = Amps X Volts, where Volts = Amps X Ohms.)

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